Nulling Interferometry and Planet Detection

Michelson Interferometry Summer School

August 11,1999

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JPL

Planet Detection

- **Indirect Methods** (= perturbations to stellar parameters):
  - Stellar Position → Astrometry
  - Stellar Velocity → Radial Doppler Shifts
  - Stellar Intensity → Transits, Microlensing

- **Direct Methods** (= direct detection of planetary radiation)
  - Direct Imaging → Large Telescopes
  - Starlight Suppresion → Coronagraphy, Nulling Interferometry

Optimal waveband for direct planet detection

- **Visible Light:**

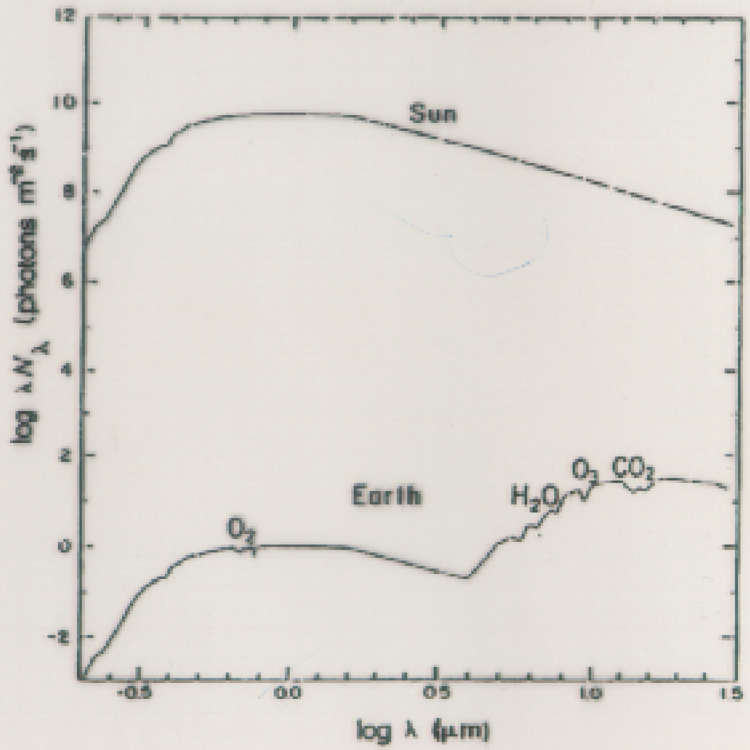
  Reflected Stellar Flux

  Contrast = $10^9 - 10^{10}$

- **Thermal Infrared:**

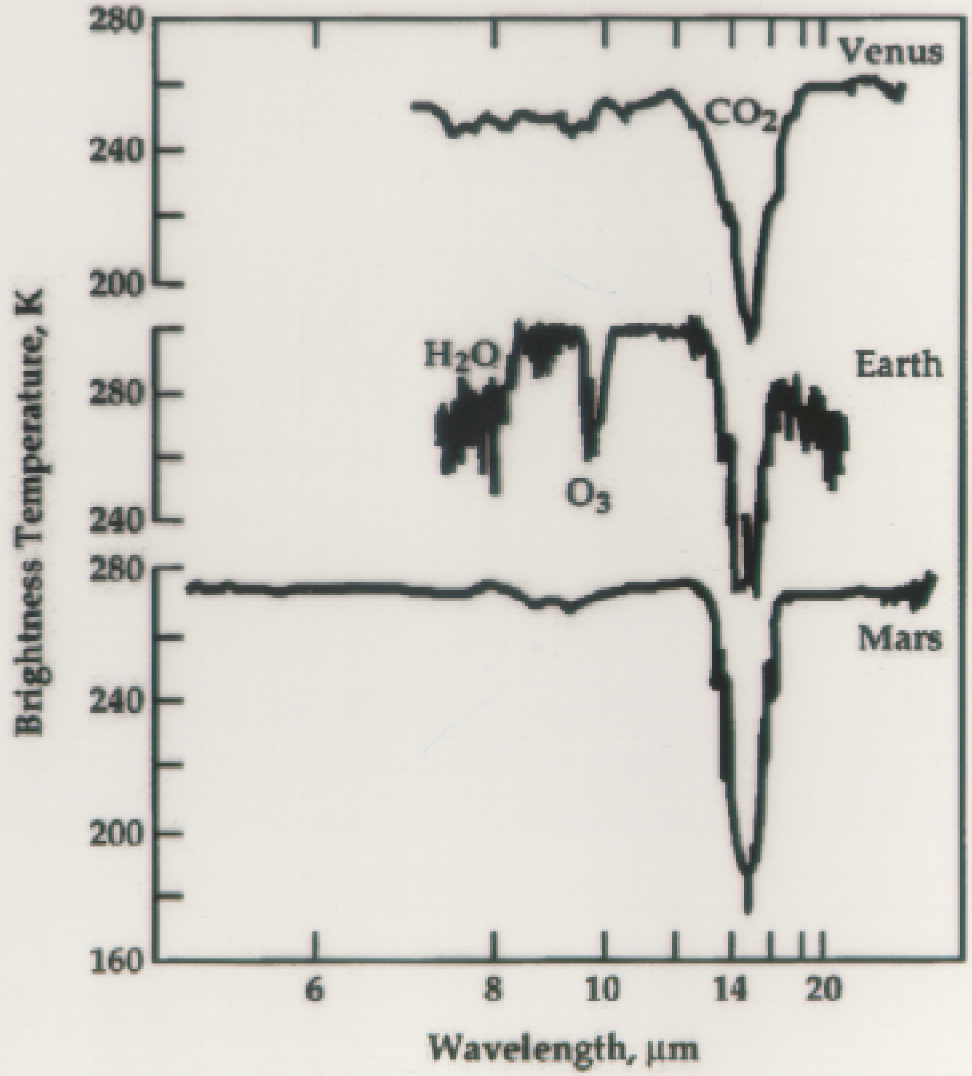
  Thermal Planetary Emission

  Contrast = $10^6 - 10^7$



Mid-infrared Spectroscopy

- Search for an atmosphere: CO_2
- Search for water
- Search for life (O_3 in lieu of O_2)



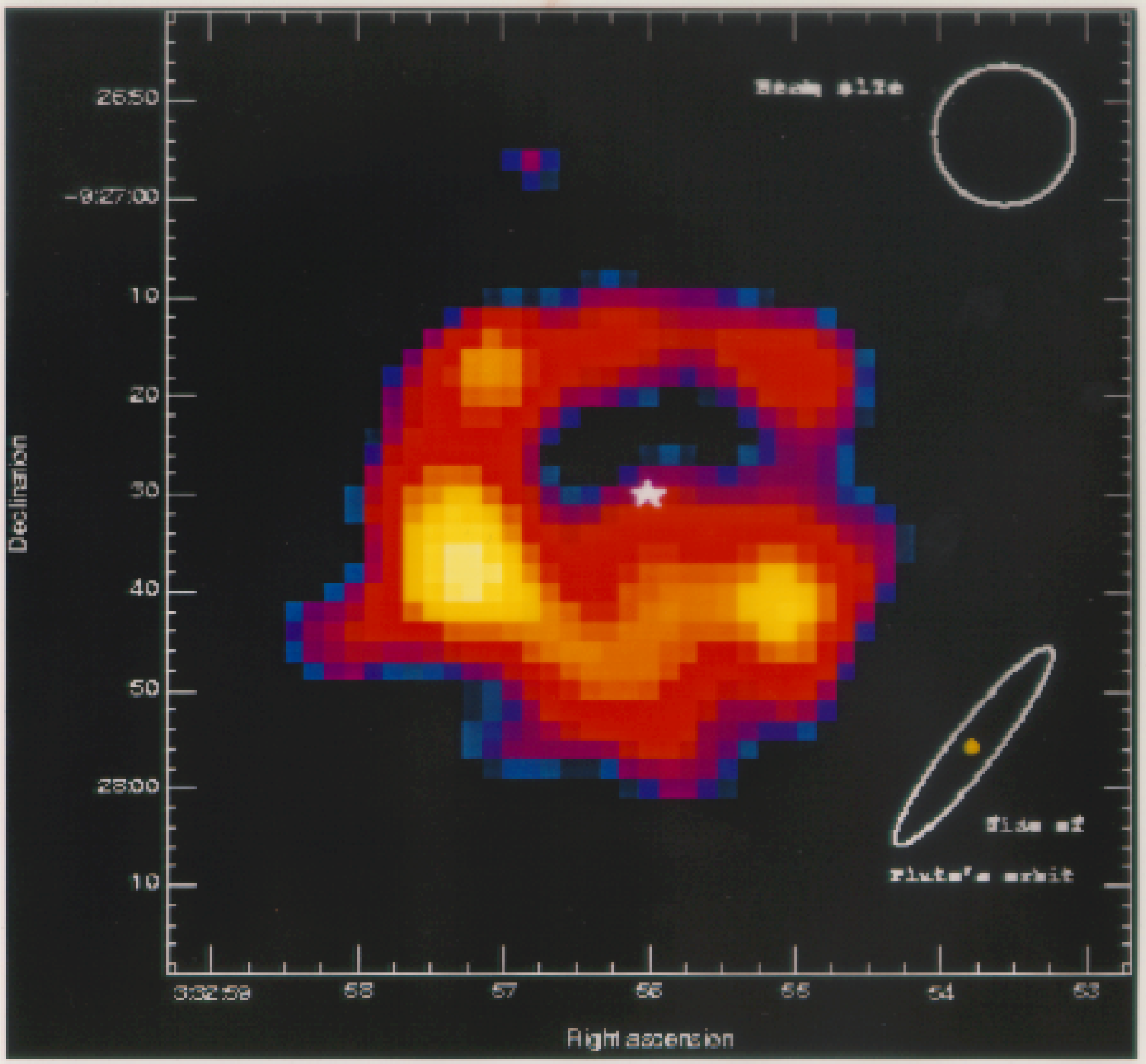
Comparison of approaches

- 1 AU ⇔ 1.0 arcsec at 1 pc
  0.1 arcsec at 10 pc
- 10-m aperture diffraction-beam at 10 m = 0.2 arcsec

- **To see an exact Earth-analog at 1 AU from its star:**
  Nulling Interferometry: $\theta < \lambda/D$ (< few 0.1 arcsec)
  stellar distance ≈ 10 pc
  Coronagraphy: $\theta > 3 - 5\ \lambda/D$ (> 1-2 arcsec)
  stellar distance ≈ 1 pc
  Direct imaging: $\theta > 10 - 20\ \lambda/D$
  telescope diameter > 20 m
- Only nulling interferometry can see in close enough to stars in the mid-infrared.

ε-Eridani
Greaves et al

Submm
JCMT



– cold Kuiper-belt-like material

Pluto's orbit

Comparison of Flux Levels

Distance = 10 pc Wavelength = 10 μm

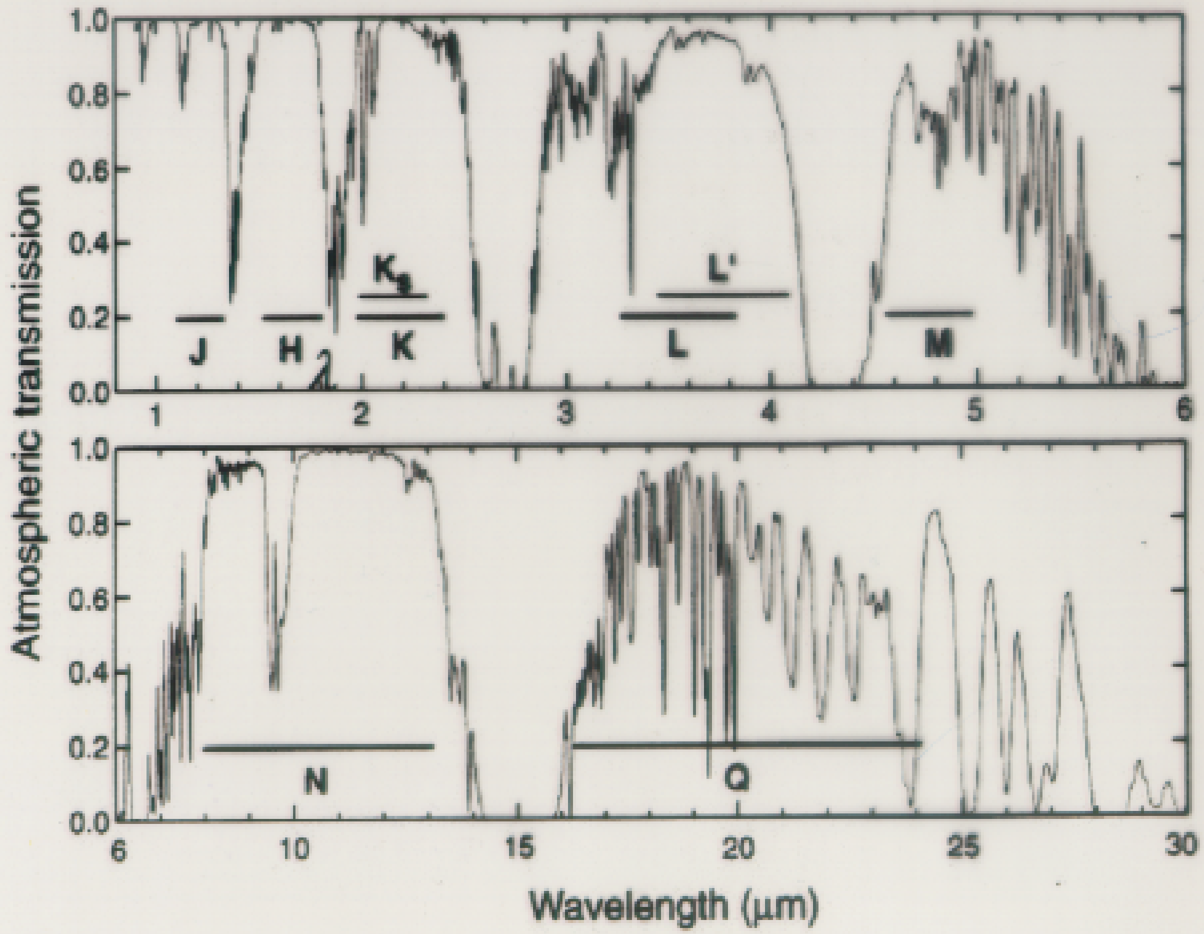
- Signals:

G2 star	2.2 Jy
Exozodiacal emission	200 μJy
Jupiter	2 μJy
Earth	0.3 μJy

- Backgrounds:

Zodiacal emission	800 μJy
Sky (emissivity = 0.1)	30 Jy

Mid-IR atmospheric window: 8-13.5 μm

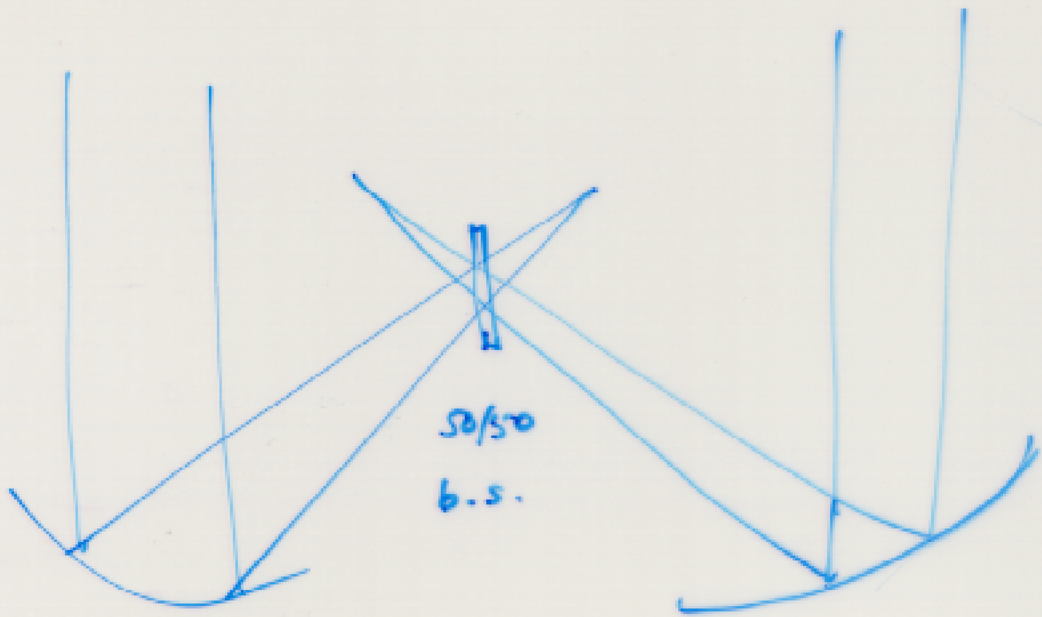


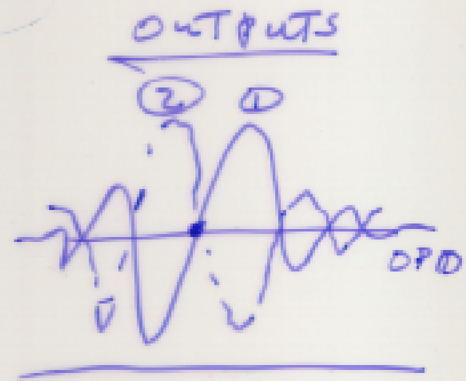
Nulling Roadmap

Target at 10 pc

- **Keck:** Characterize exozodiacal MIR emission around nearby stars.
  - In our solar system, integrated zodiacal light at 10 μm is
    10^{-4} of solar flux
    10^{-6} of background
  - Null star and remove background.
- **SIM:** demonstrate optical nulling with nm-level control, as needed by TPF.
  – 10^{-4} null @ 1 μm ⇔ 10^{-6} null @ 10 μm
- **TPF:** detect planets at 10 μm in the presence of stellar, zodi, and exozodi signals. 10^{-6} null across MIR (7-20 μm) .

Nulling Interferometry

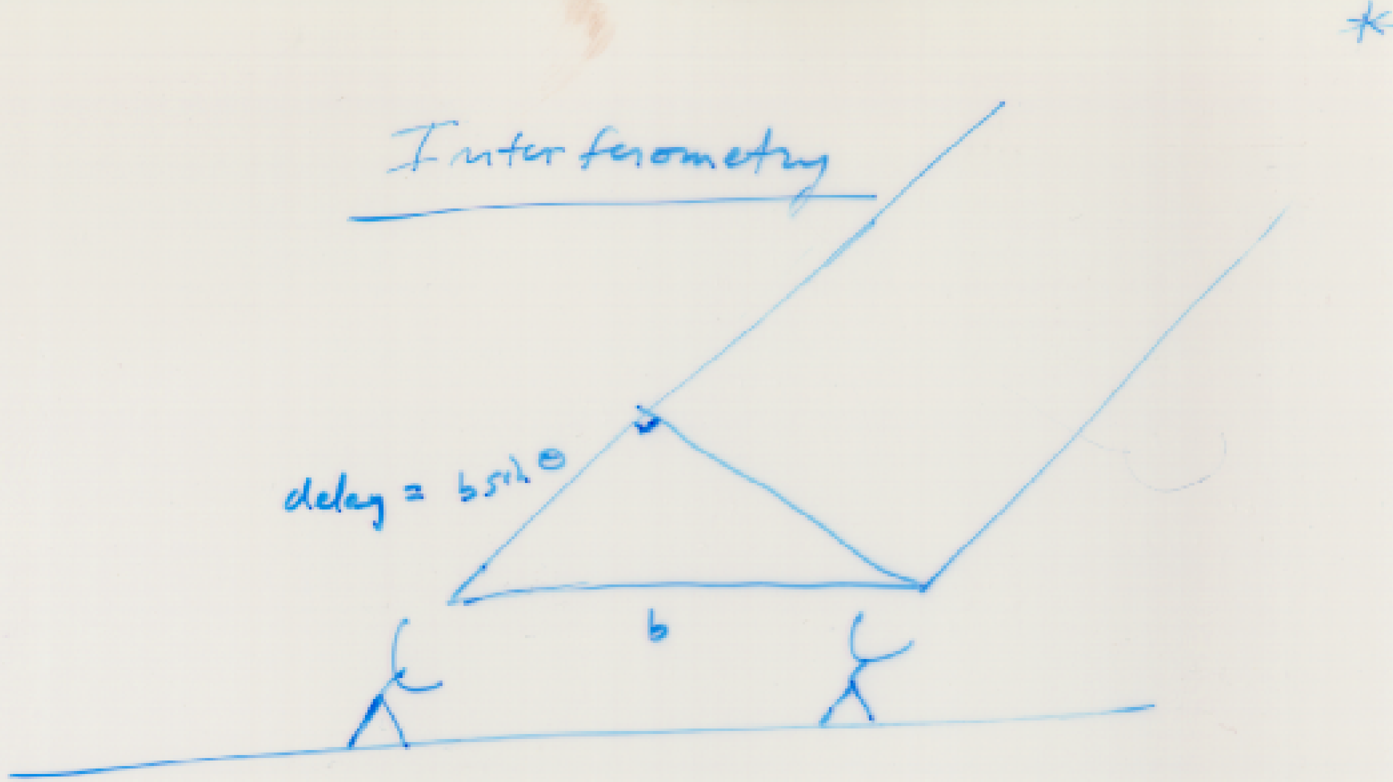


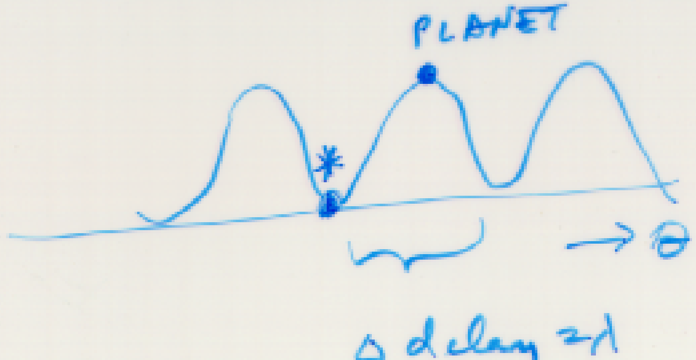


Combine the light from two telescopes 180° out of phase.

Bracewell & MacPhie (1979) Icarus

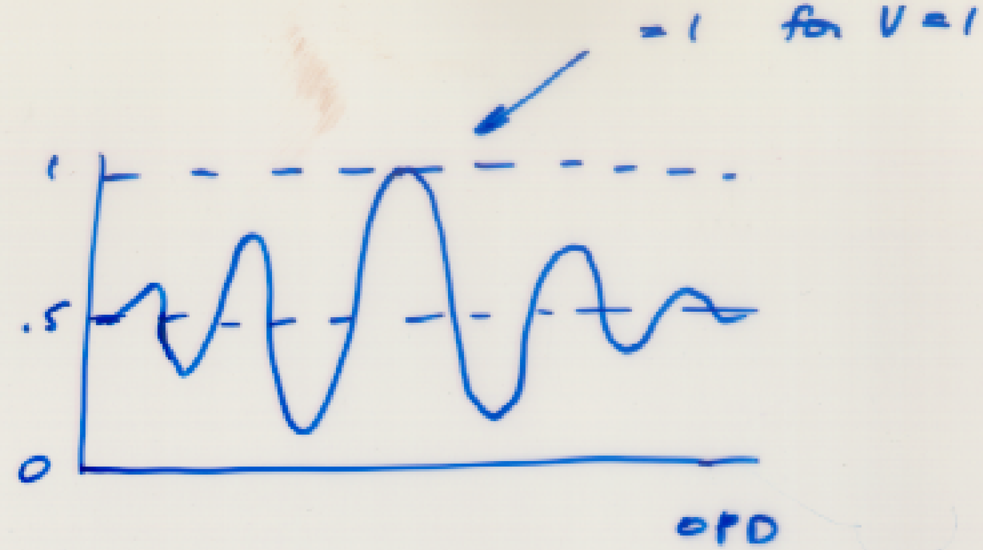
Interferometry



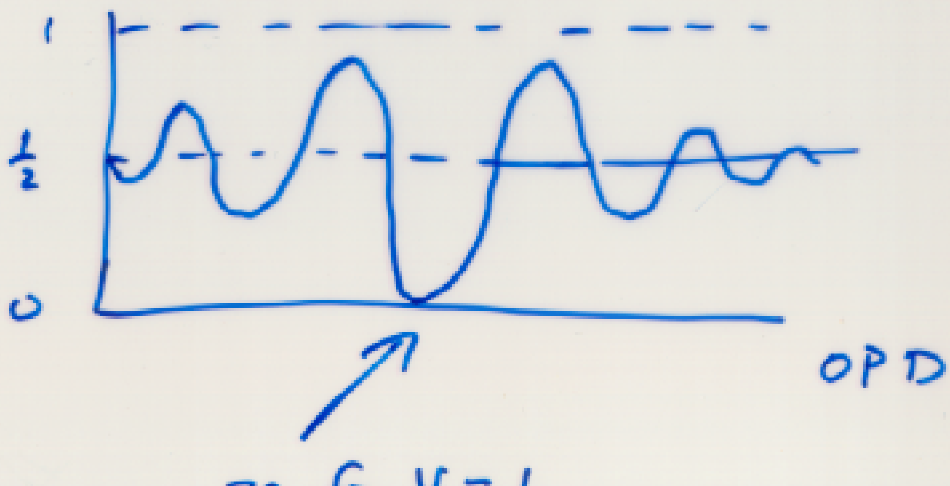


At star position,
$E_1 - E_2 = 0$
for all λ's.

CHANGE

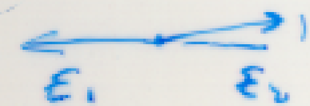


TO



General achromatic nulling requirements

- For a deep, achromatic null (SIM - 10^{-4}, TPF - 10^{-6}), simultaneous cancellation of the **E** field must occur at all wavelengths in the band
- High degree of matching required:
  - **E** fields in the two input beams opposite in direction.
  - Intensities matched.
  - Relative path delays zero.

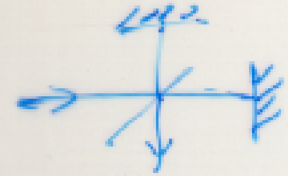


- Matching must be maintained across the passband.
- BW evolution: SIM 20%, Keck 30 - 50%, TPF 100 %.
- Single spatial mode operation to remove wavefront aberrations:
  - Wavefront quality limits null depth to 1-S, or about 4%.
  - Single mode fiber (optical) or pinhole (MIR) spatial filter required.
- Experimental validation of nulling concepts necessary.

Achromatic nulling

- Normal ``constructive" 2-beam interferometer:

$$I_{\text{out}} = I_{\text{in}}(1+V\cos\varphi)/2$$



- Bandwidth limitation to destructive interference minima:

$$\frac{I_{\min}}{I_{\max}} = \frac{1}{2}\left(1-\operatorname{sinc}\frac{\pi}{2}\frac{\Delta\lambda}{\lambda}\right)$$

- For bandwidths = 5, 10, 20, 30, 40, 50%,
  deepest destructive interference =
  0.05, 0.2, 0.8, 1.8, 3.2, 5%.
- Deeper cancellation requires achromatic approach,
  e.g. a relative field flip:

$$I_{\text{out}} = I_{\text{in}}(1-V\cos\varphi)/2$$

Null Depth Definition

- Null depth : $$N \equiv I_{\min} / I_{\max}$$
  where I_{out} and I_{in} are the nuller throughputs in the destructive and constructive states, repsectively.

- In terms of visibility, for perfect phase matching,

$$N = (1-V)/2.$$

- For V=1 and small phase errors, φ,

$$N = (\phi / 2)^2$$

- Both V<1 and $\phi \neq 0$ limit null depth and so drive the requirements.

- Example: For N = 1e-4, V= 0.9998.

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OPD Accuracy Needed: $\phi = 2\pi x_{OPD}/\lambda$

$$N = \left(\frac{\pi x_{OPD}}{\lambda}\right)^2$$

$$\frac{x_{OPD}}{\lambda} = \frac{1}{\pi}\sqrt{N}$$

Take $N_{OPD} = 3 \times 10^{-5}$

$x_{OPD} \sim \lambda/600$

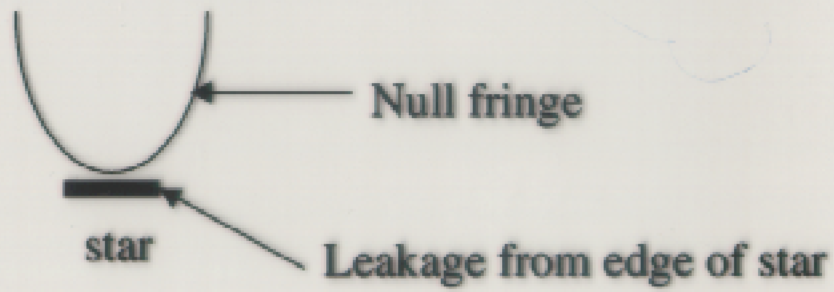
~ 1 nm @ $\lambda = 600$ nm

~ 16 nm @ $\lambda = 10$ μm

How deep is your null?

- Fundamental limit: Nonzero stellar diameter limits N to:

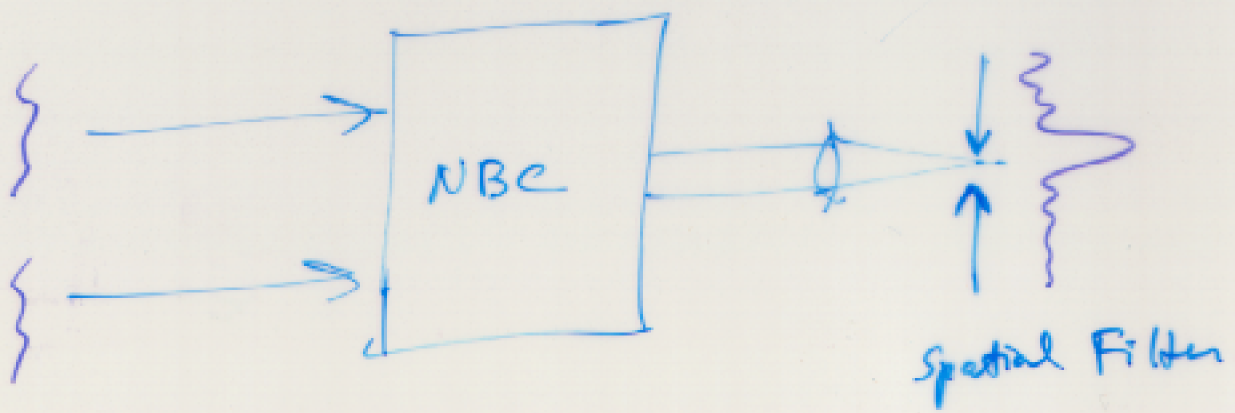
$$N = \frac{\pi^2}{16}\left(\frac{\theta_{dia}}{\lambda / b}\right)^2$$



- For a G star @10 pc, with an angular diameter of 0.93 mas, N=3e-5 at 0.7 mu requires a projected baseline of < 1.1 m.
- A reduction in flux by 1e-4 corresponds to 10 magnitudes: On SIM, this leaves a flux of order 1000 ph/s/aperture.
- For a G star @10pc @ Keck $N \sim 10^{-3}$

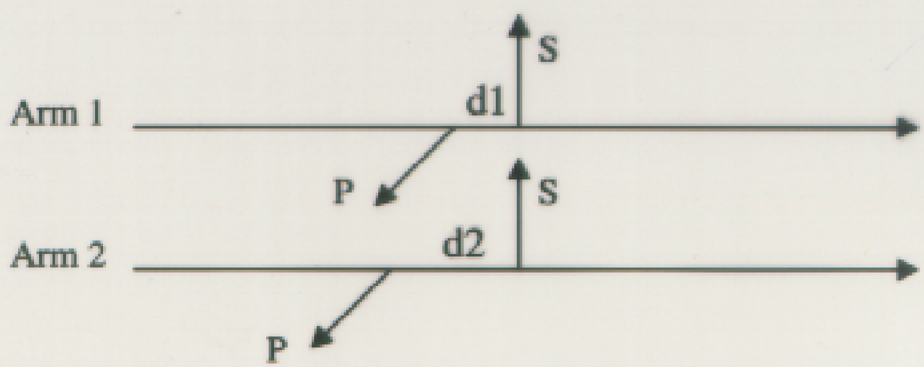
Wavefront Cleanup

- Aberrated wavefronts prohibit simultaneous field cancellation across the wavefront. N limited to about 1-S.
- Wavefront cleanup required for deep nulls
- Wavefront cleanup can be effected by means of a spatial filter in the output focal plane, which transmits only the core of the point-spread function.
- Limits nulling to a single spatial mode of the telescope.



Sources of null degradation

• Finite Stellar Diameter	Static
• Nonunity visibility:	
- Wavefront errors - removed by spatial filtering	Static
- Polarization rotation mismatch	Static
- Intensity mismatch: transmission asymmetries,	Static
pointing jitter induced scintillations	Fluctuating
• Nonzero phase:	
- Optical path jitter	Fluctuating
- Differential s-p polarization delay (d1-d2 below)	Static
• Chromatic Effects	Static

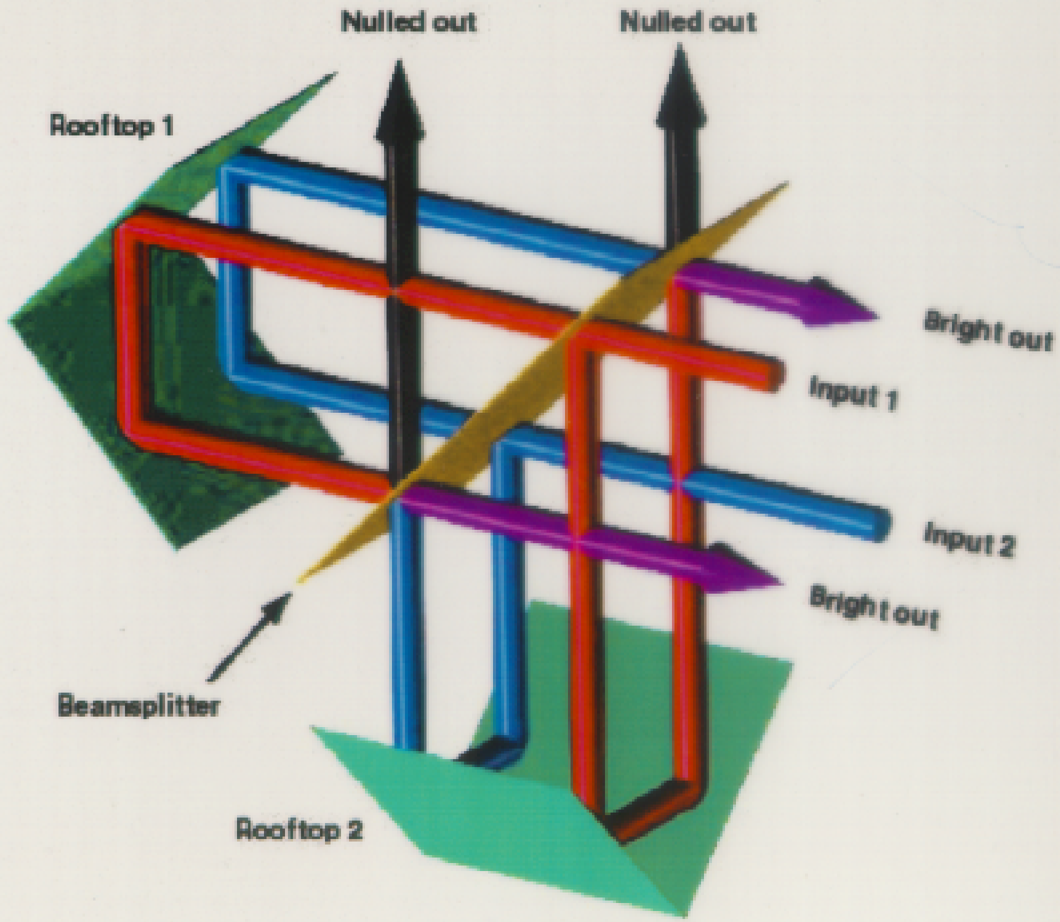


Electric Field Manipulation

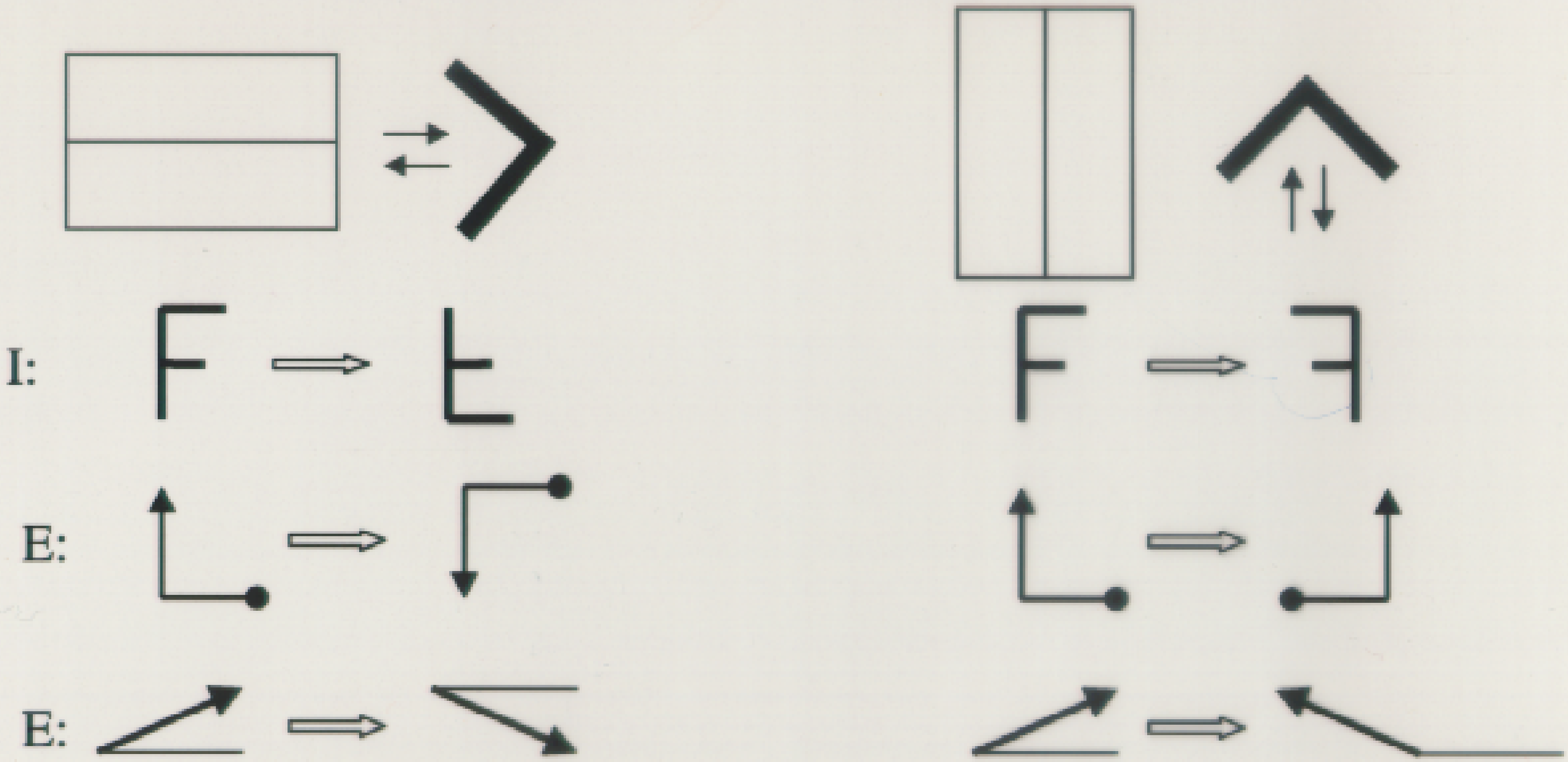
- **Electric field reversal can be effected by means of:**

- Geometric field flip: rotational shearing interferometer
- Through-focus field flip: (RSI)
- Phase retardation: chromatic waveplate

Beam Combination in an NBC

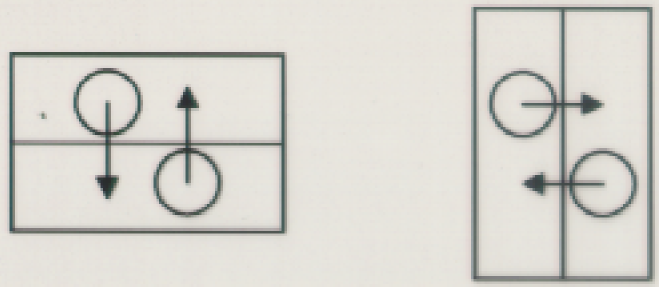


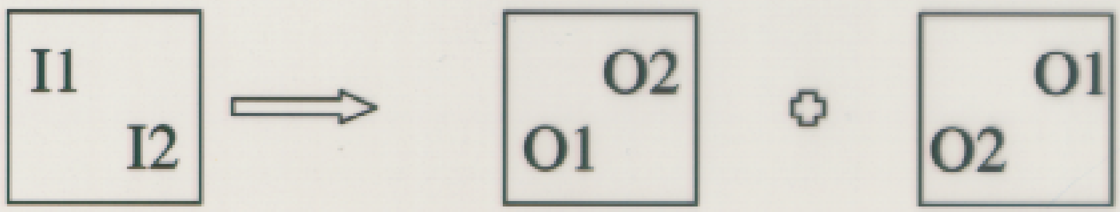
Orthogonal Rooftop Mirrors



- Electric field vectors orthogonal to rooftop axis flipped by 180 degrees.
- Electric vectors parallel to rooftop axis unchanged.
- Output beams have polarizations rotates 180 deg. w.r.t. each other.
- Output apertures are rotated 180 deg. w.r.t. each other.

Interferometer Nuller



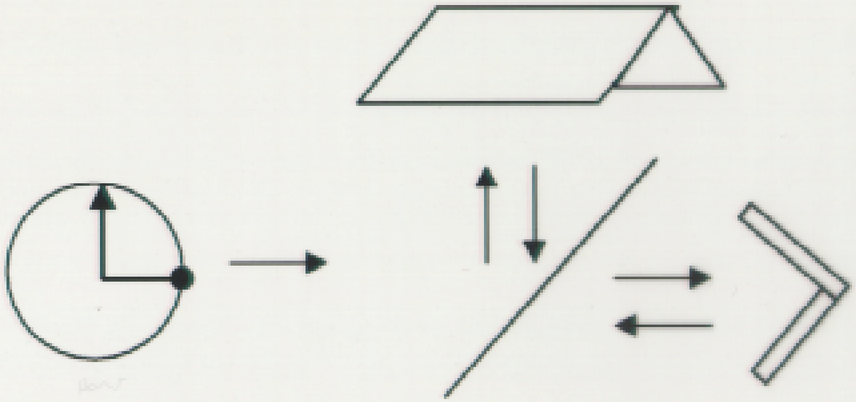


Inputs

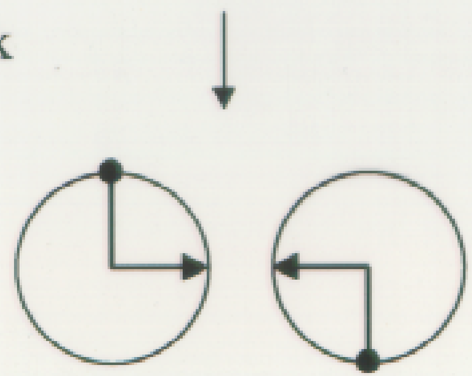
Twin Outputs on either side of beamsplitter

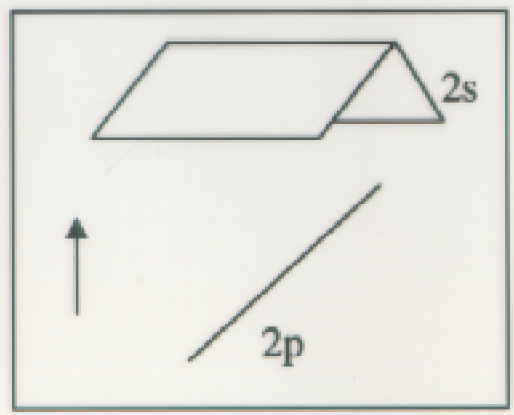
Additional Complications

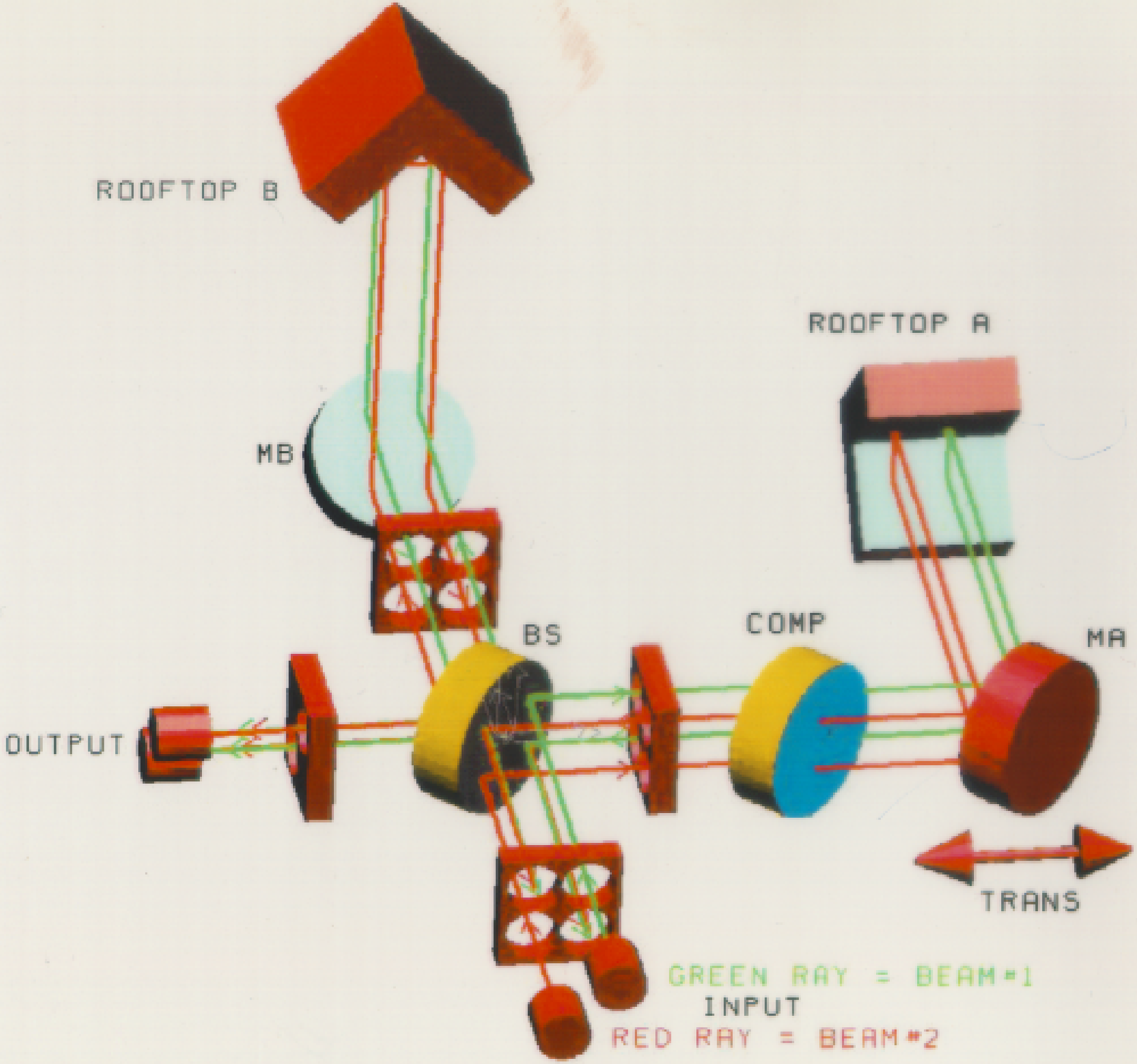
- Output images and electric fields rotated by 180 deg.
- Asymmetric: one arm has 2 s reflections, other has 2 p refl.
- Add fold mirror in each arm to symmetrize reflections:



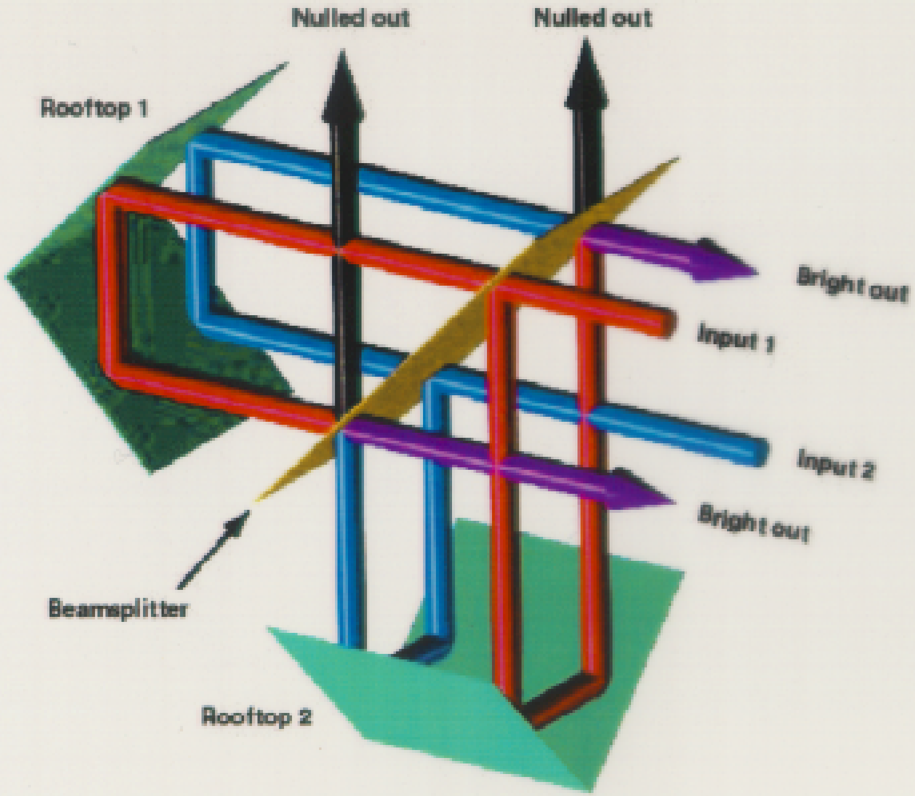
Views looking back into the beam






ROOFTOP B
ROOFTOP A
MB
BS
COMP
MA
OUTPUT
TRANS
GREEN RAY = BEAM #1
INPUT
RED RAY = BEAM #2

Implementation: rotational shearing interferometer



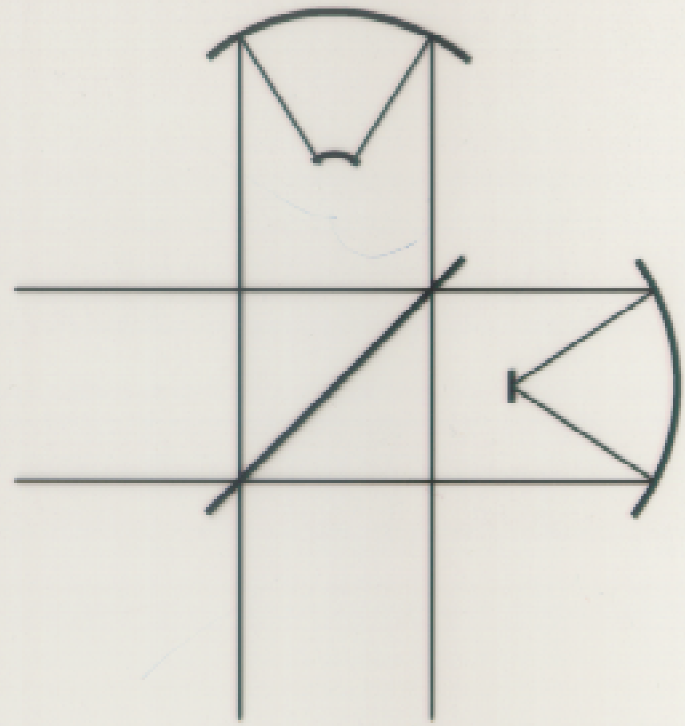
- Advantages:
- Nearly perfect symmetry
- Relies solely on flat mirrors
- Achromatic, geometric π phase flip
- High R/T ratio tolerance at 2-pass b.s.
  (nulling outputs are both balanced
   RT outputs)
  (R near 0.5 only maximizes throughput)

- Drawbacks:
- High quality rooftop reflectors needed

- Both:
- 2 outputs

Implementation 2: Phase shift through focus

- Passing through focus inverts aperture, adds achromatic 180 deg phase shift.
- Replace rooftops by cat's eyes:
  - one secondary flat, at focus
  - other secondary curved, prior to focus
- Advantages:
  - Achromatic 180 degree phase flip
  - Phase flip orthogonal to OPD
  - Relaxed b.s. R/T requirements
- Disadvantages:
  - Differing angles of incidence on secs.
  - Point focus on flat secondary



Implementation 3: Waveplate (UofA)

- Dielectric plate compensates for b.s.; also adds 90 degree phase shift.

  Additional 90 deg. occurs at 50/50 b.s.
- Advantages:

  - simple layout

  - no wavefront inversion

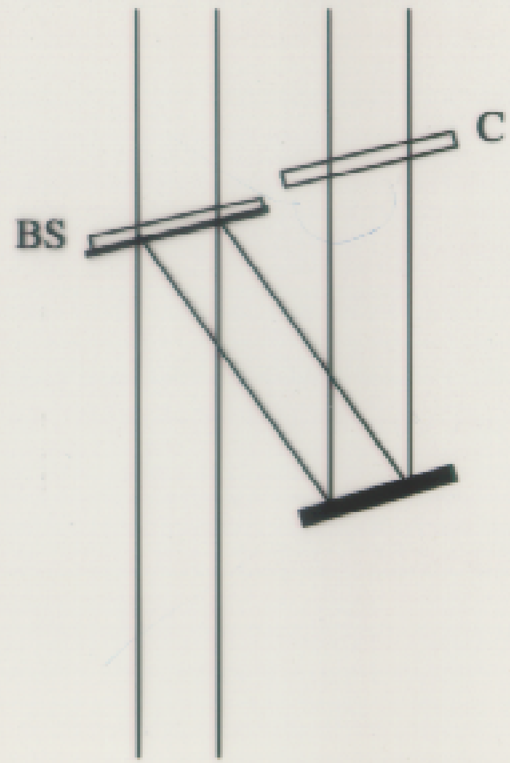
  - fewer outputs
- Challenges:

  - Requires highly accurate coatings:

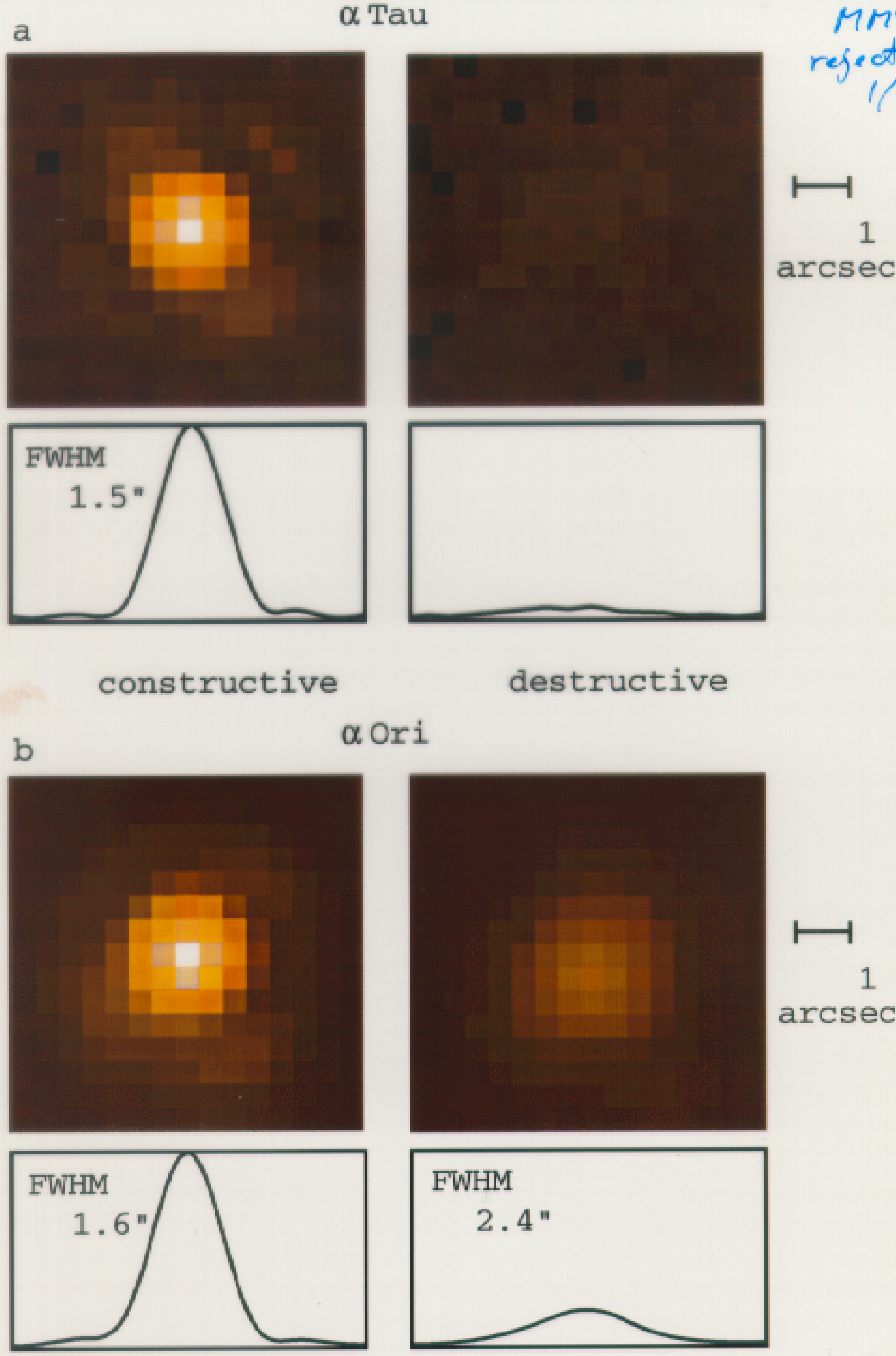
    nearly perfect R/T match needed

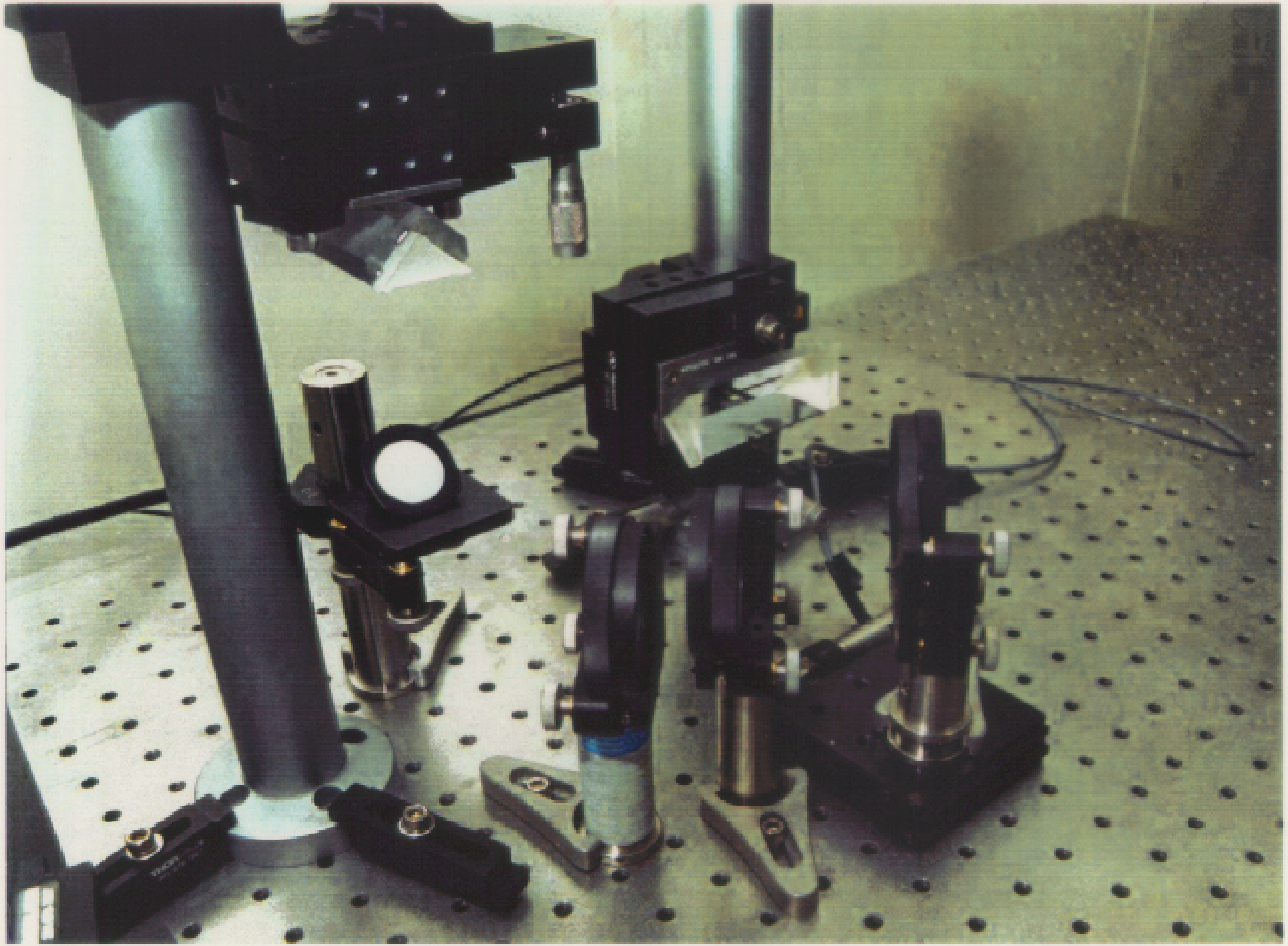
  - Requires high-accuracy tailoring of compensator refractive indices.

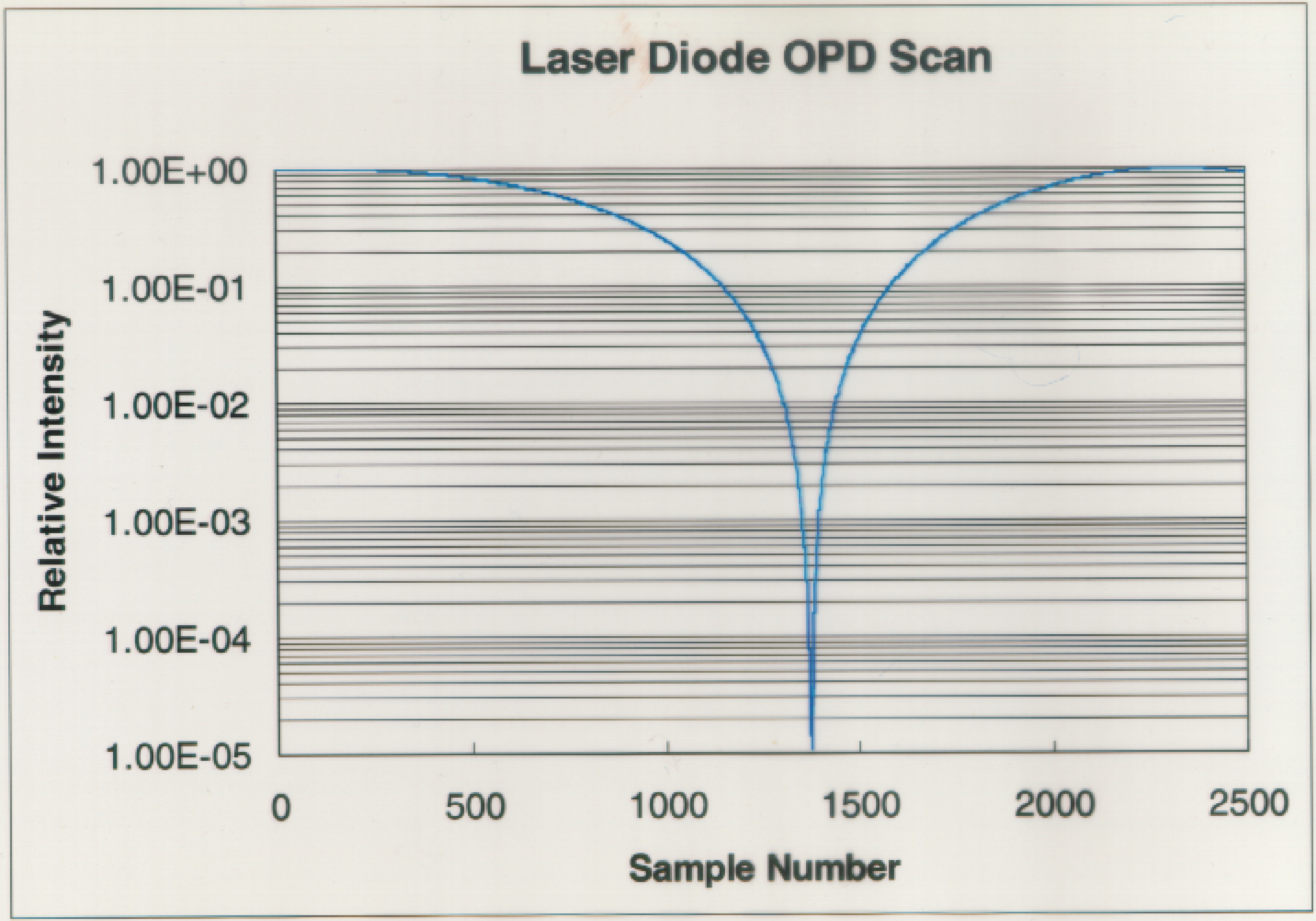
  - Phase flip and OPD not orthogonal.



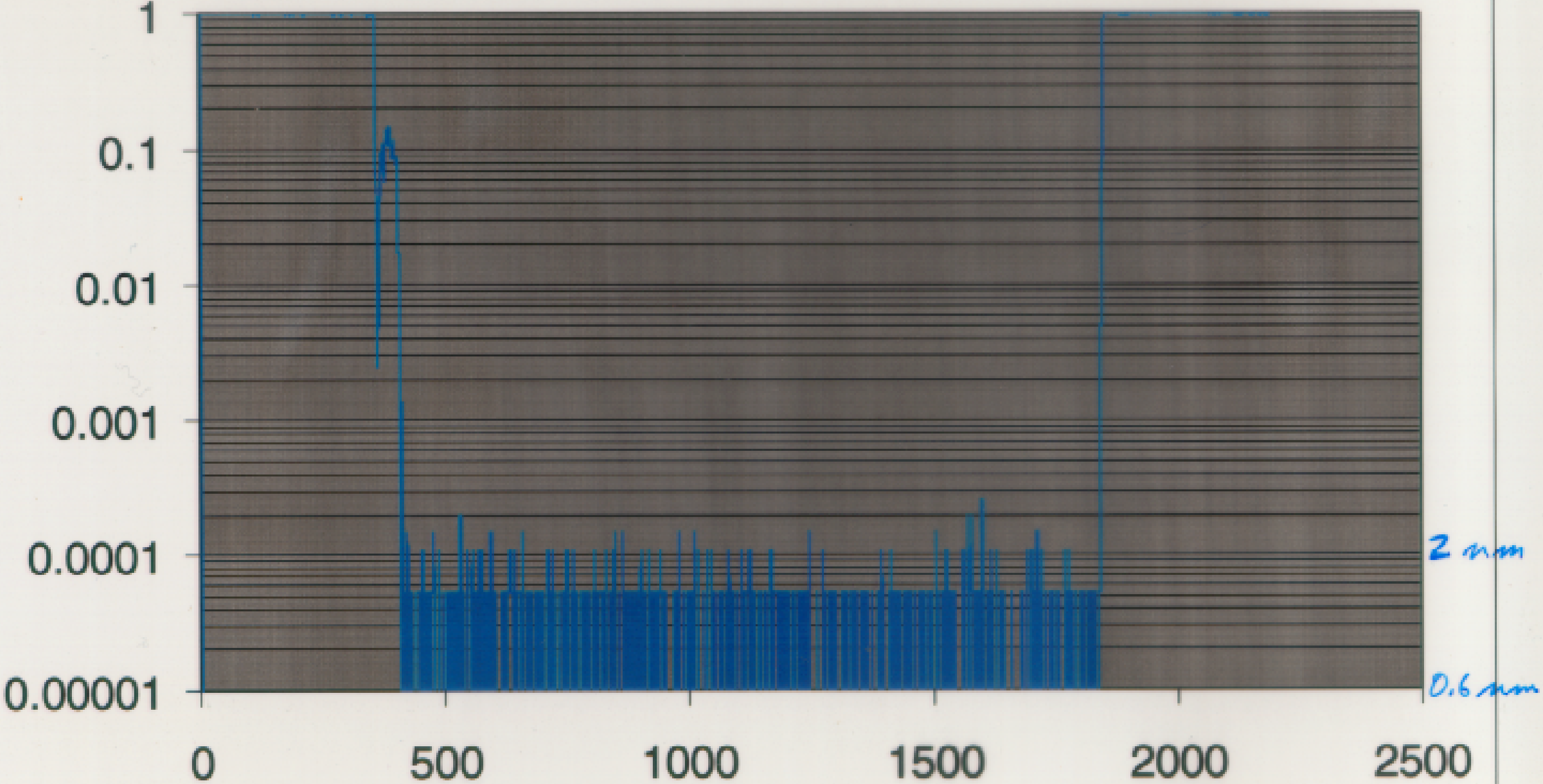
Hinz et al
MMT
rejection =
1/24



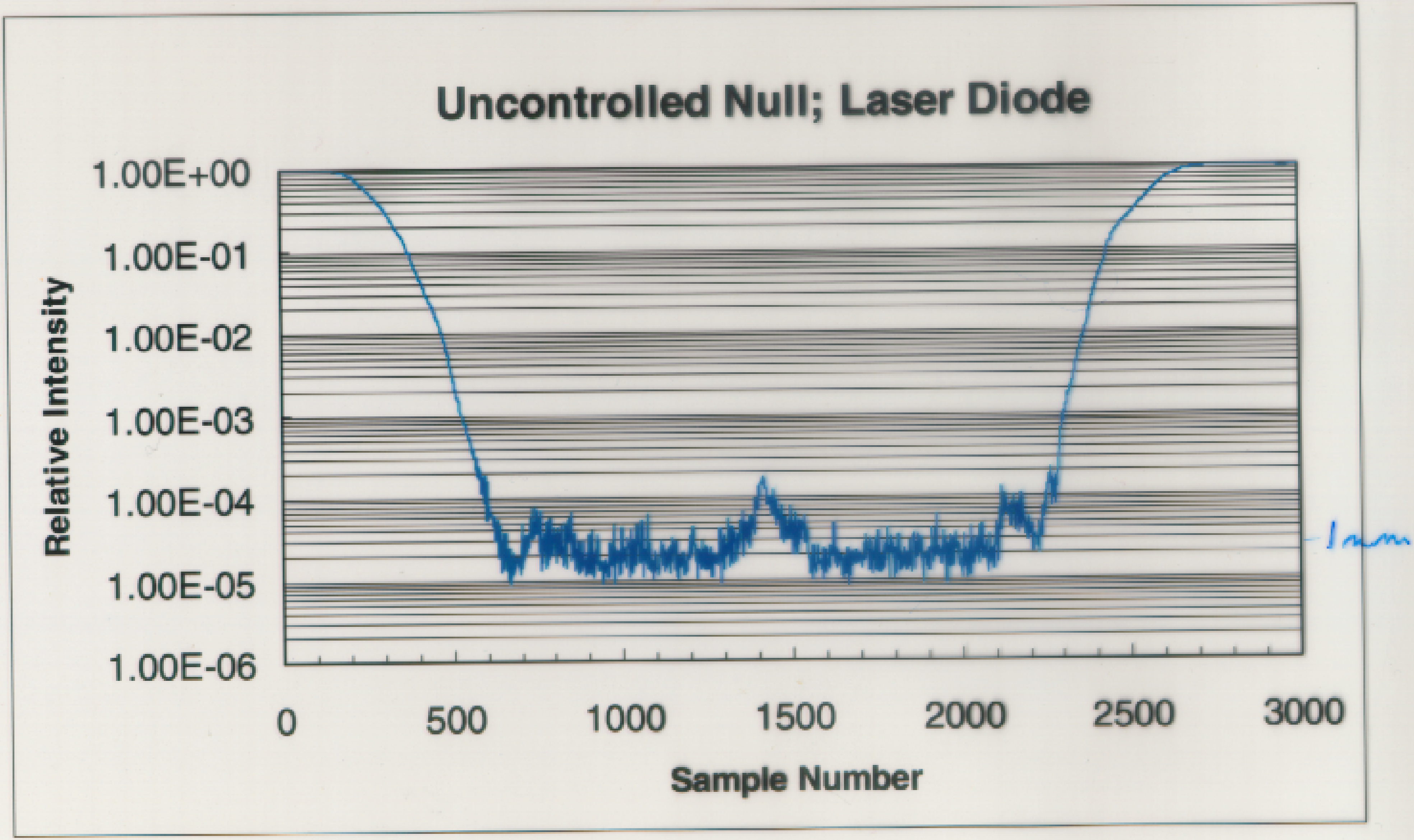


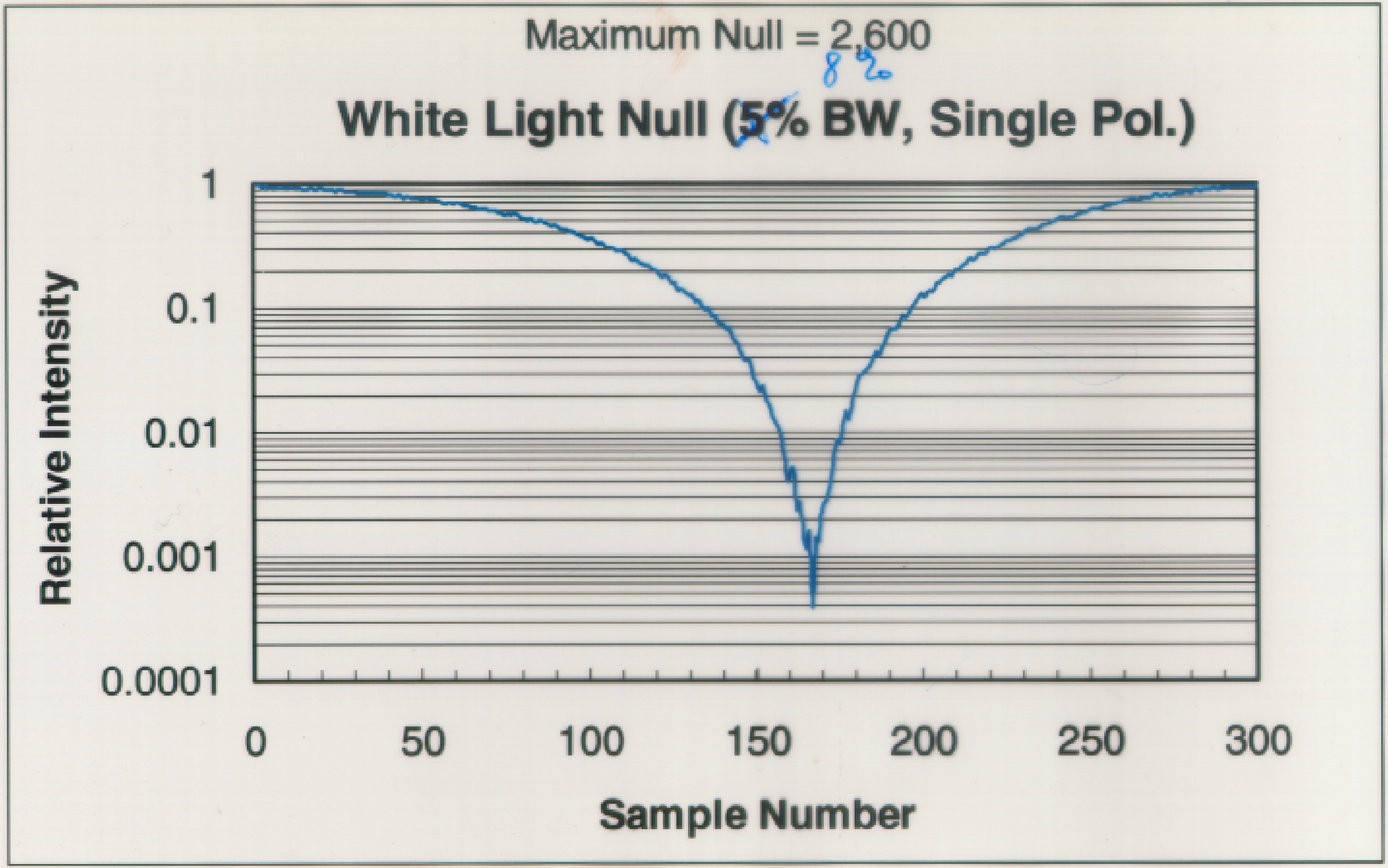

Laser Diode OPD Scan
Relative Intensity
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
0
500
1000
1500
2000
2500
Sample Number

Laser Diode, Controlled Null, May 27, Run #11

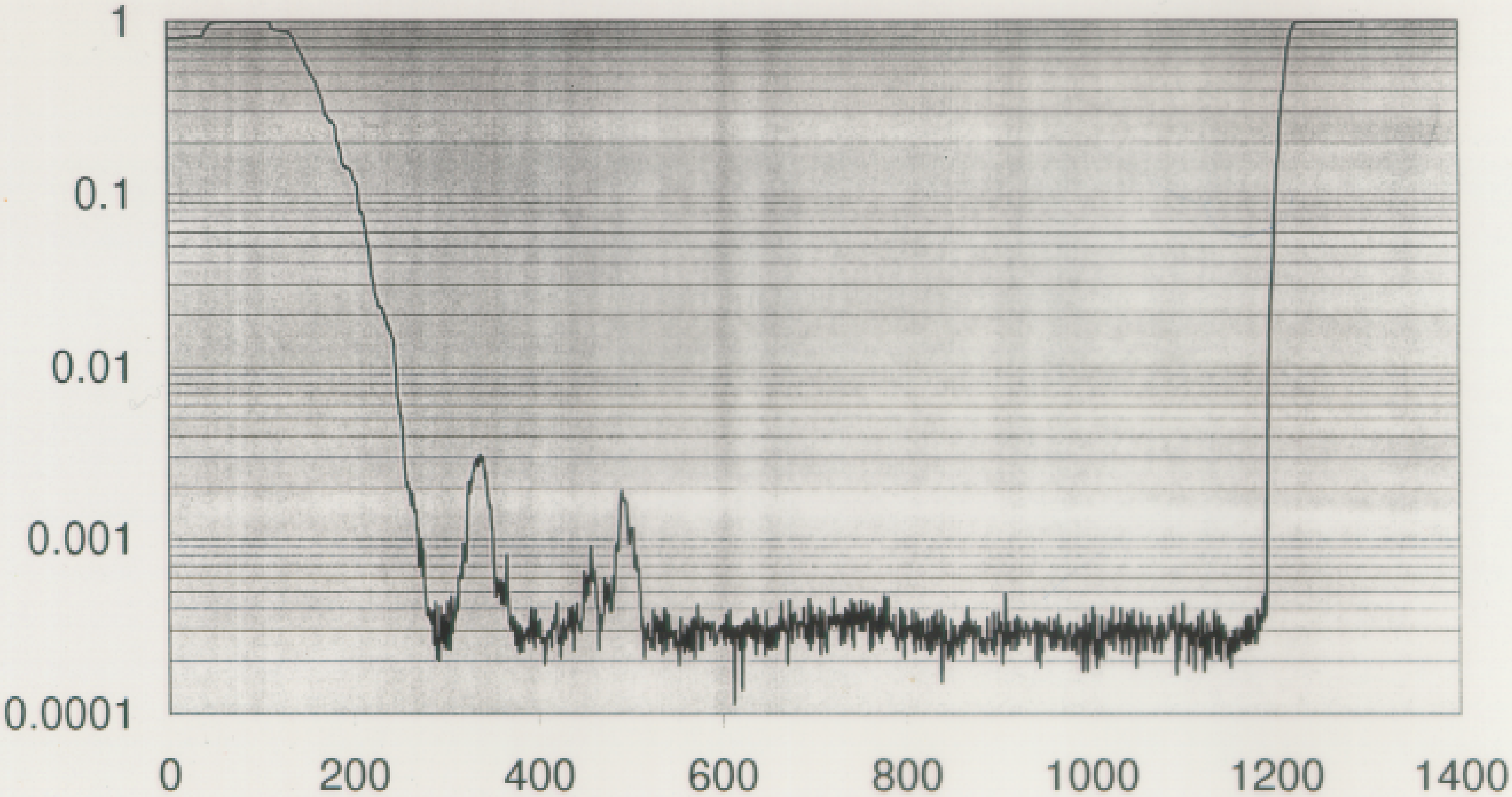


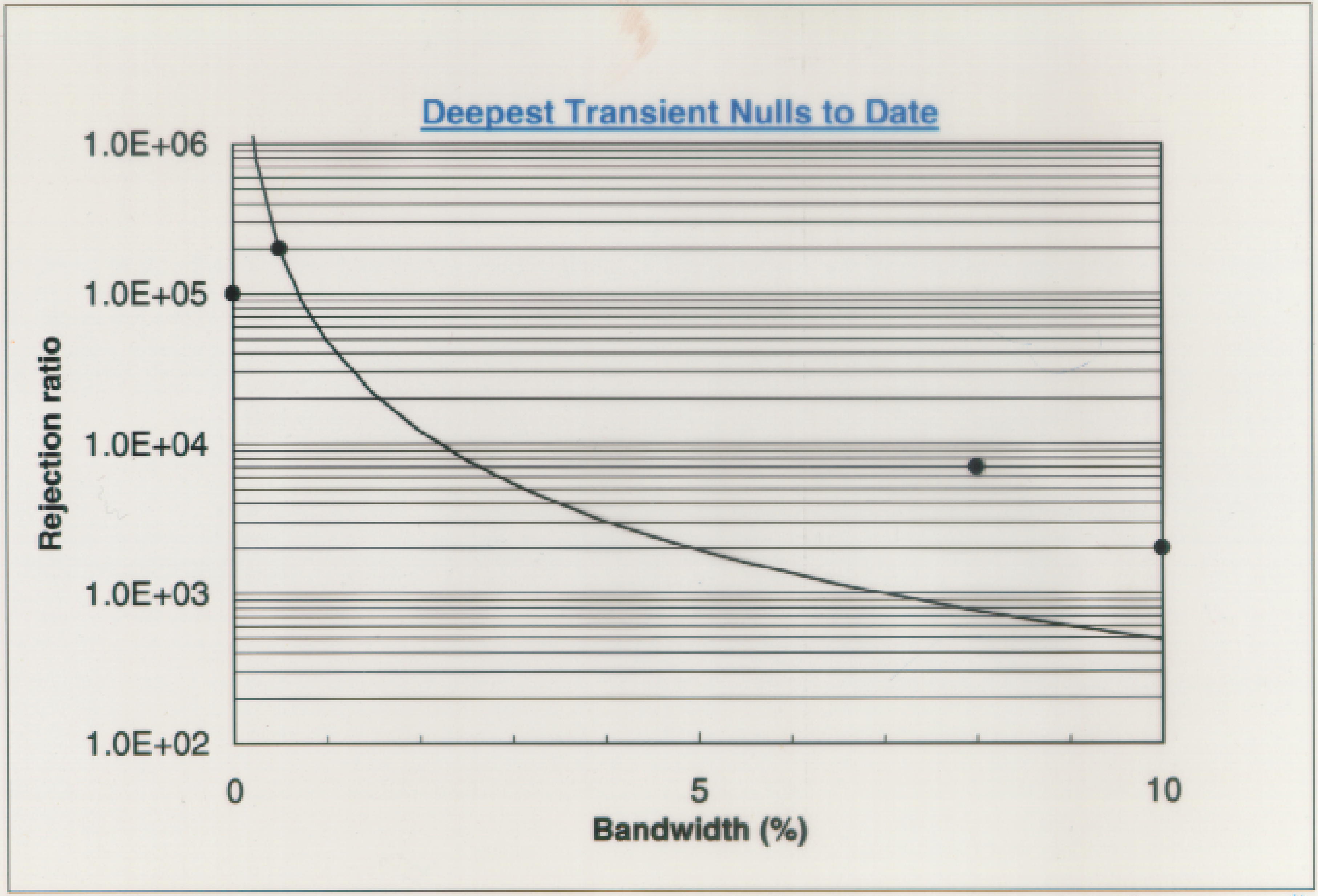
Environmental Improvements in New Lab:




Maximum Null = 2,600
8%
White Light Null (~~5~~% BW, Single Pol.)
Relative Intensity
1
0.1
0.01
0.001
0.0001
0
50
100
150
200
250
300
Sample Number

8% BW W.L. Null (1-pol).





SIM desires 10^4, 20% BW

Status

Laser diode (0.5% BW):

• Transient nulls during OPD fluctuations:	1/200,000
• Stable (average over 10 sec) null:	1/50,000
• Controlled null (peak over minute timescales):	1/10,000

Single-polarization, 8% BW white light:

• Stable (average over 10 sec) null:	1/3,000
• Best transient null:	1/7,000

OPD Control

- Control one output by means of another
- Control one waveband by means of another
- Use metrology

SIM OPD control

- **Approach:** The nuller has 2 outputs. Use 1 output to control the 2nd.
- **How?**

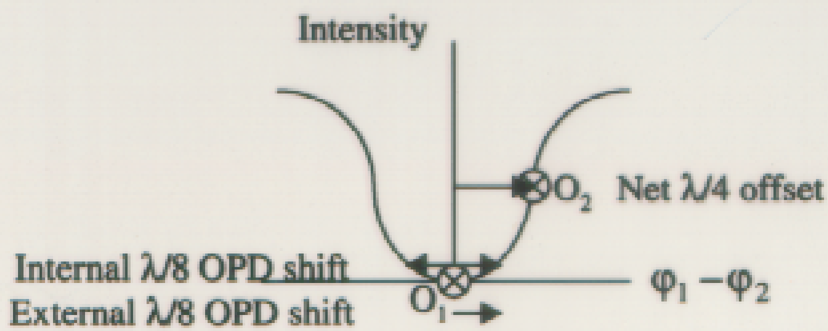
  An OPD increment in one arm of the nulling combiner affects the 2 nuller outputs in opposite senses:

  Output 1 has E_1 ahead of E_2; output 2 has E_2 ahead of E_1.

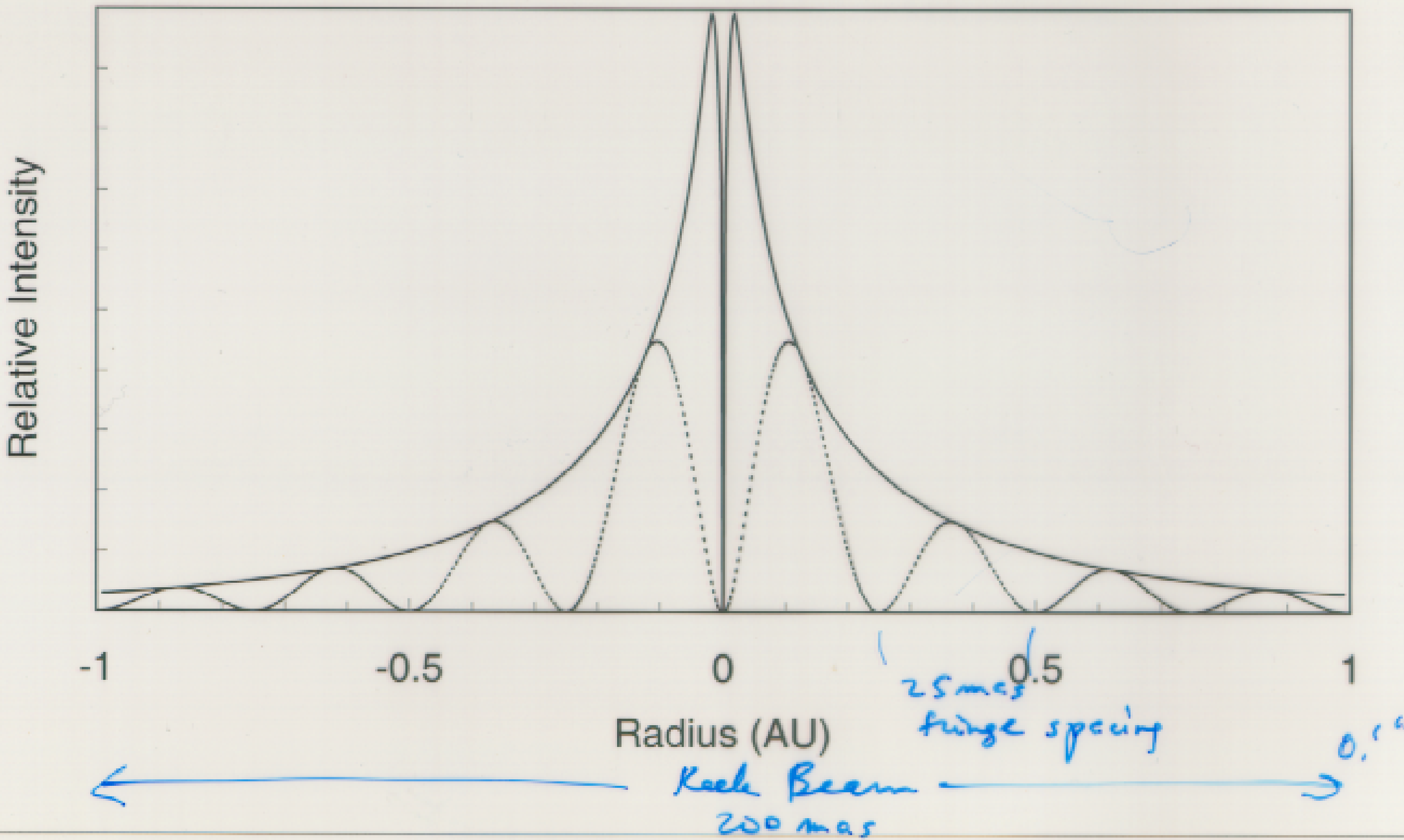
  - I.e., an *internal* nuller path delay causes the two nuller outputs to depart from null in opposite directions (opposite relative phases).

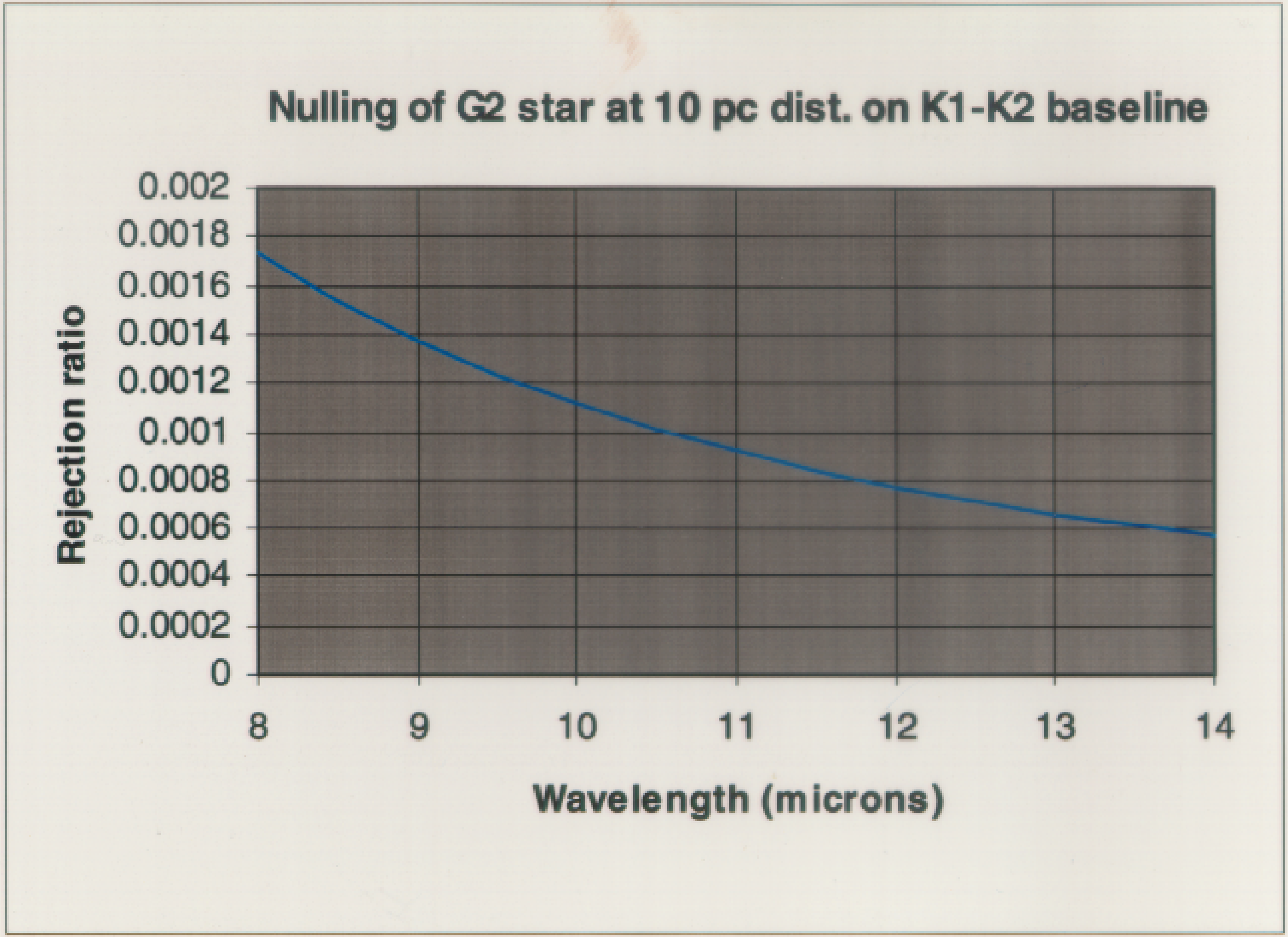
  - An external path delay (i.e., prior to the nulling combiner) always advances one beam relative to the other.

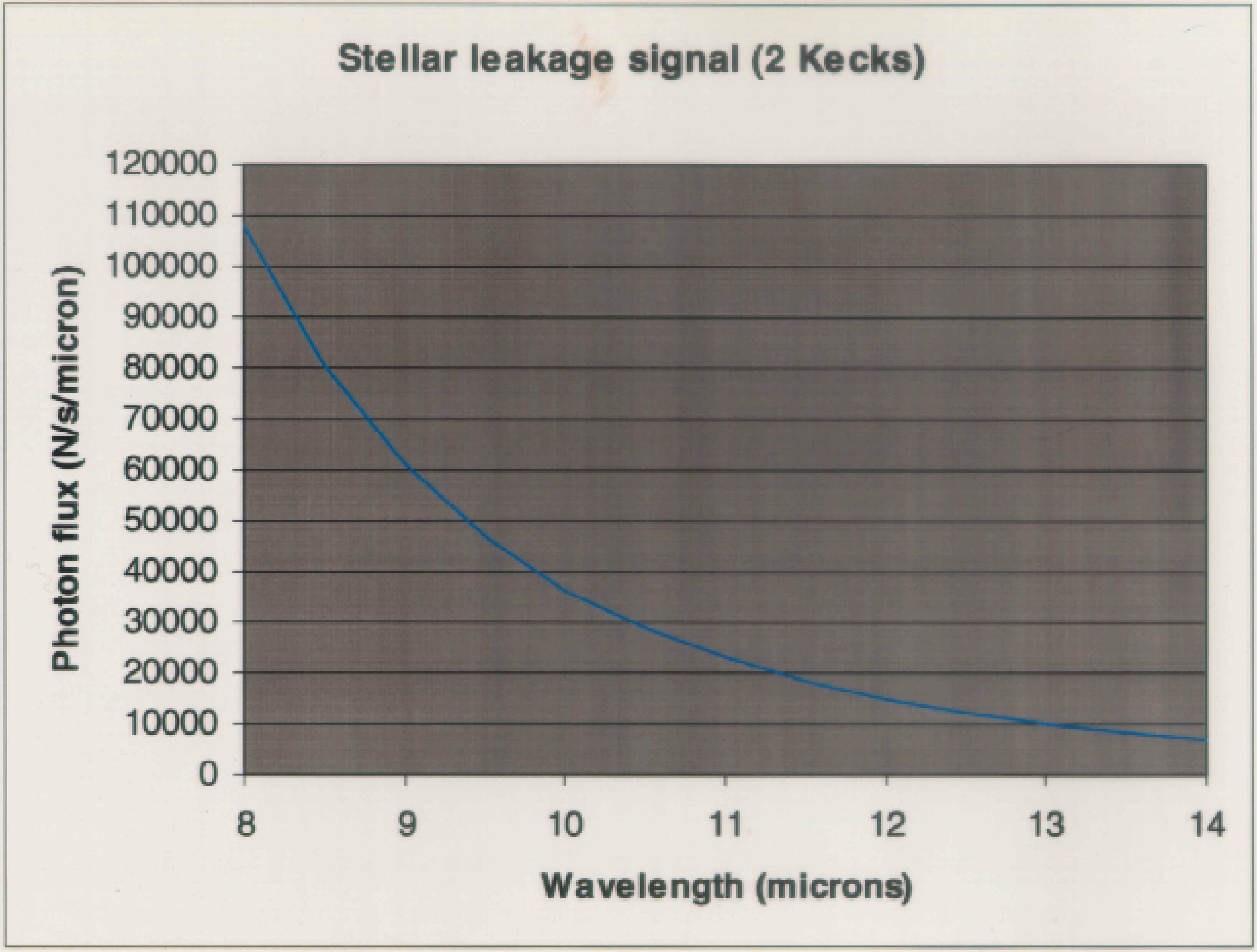
- ∴ The 2 types of offsets can be combined to leave one nuller output on null, while the second output is offset λ/4 away in OPD, where plenty of photons and a linear intensity-OPD relation are available for control.



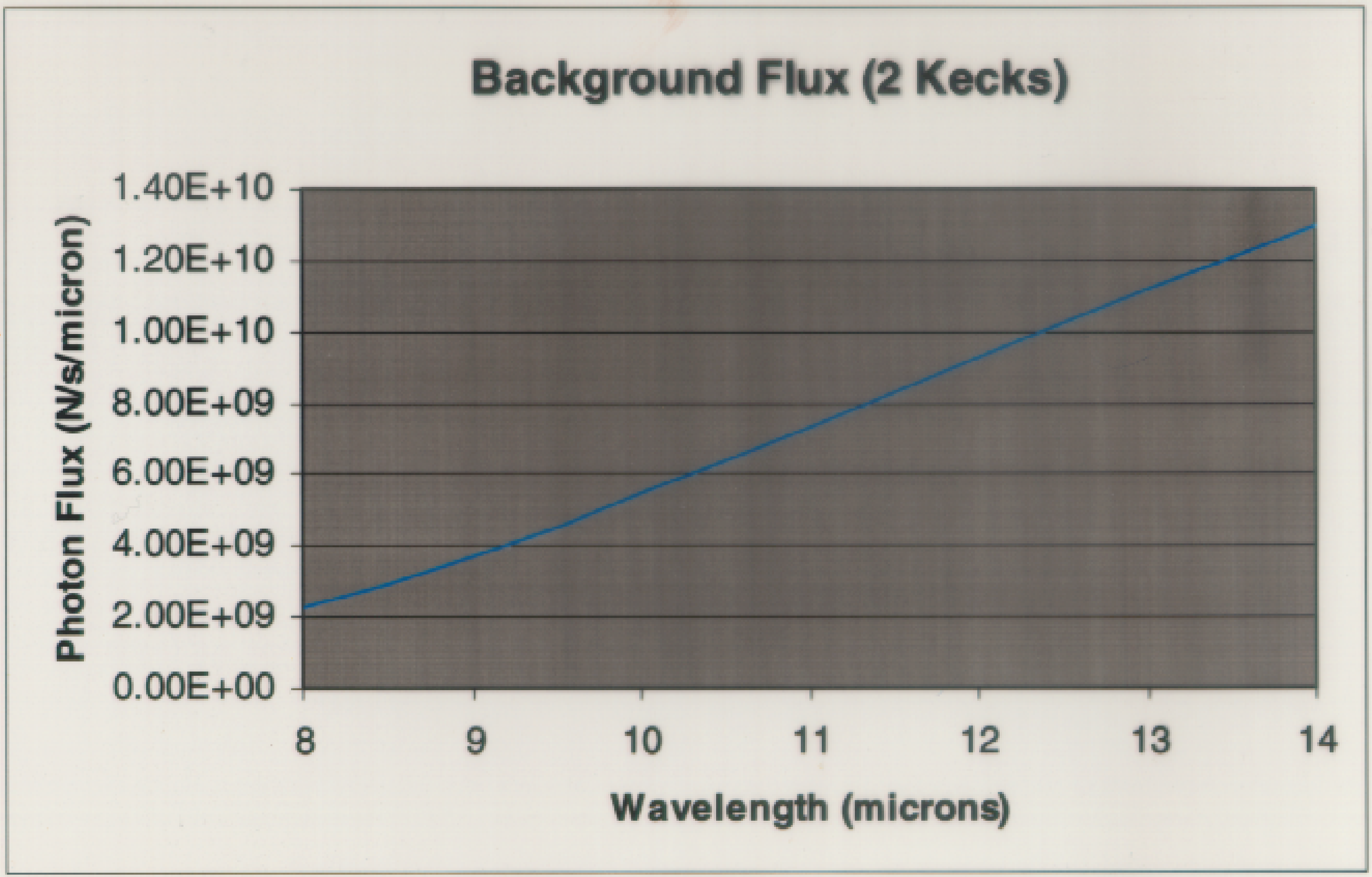
Slice Through Exozodi Disk

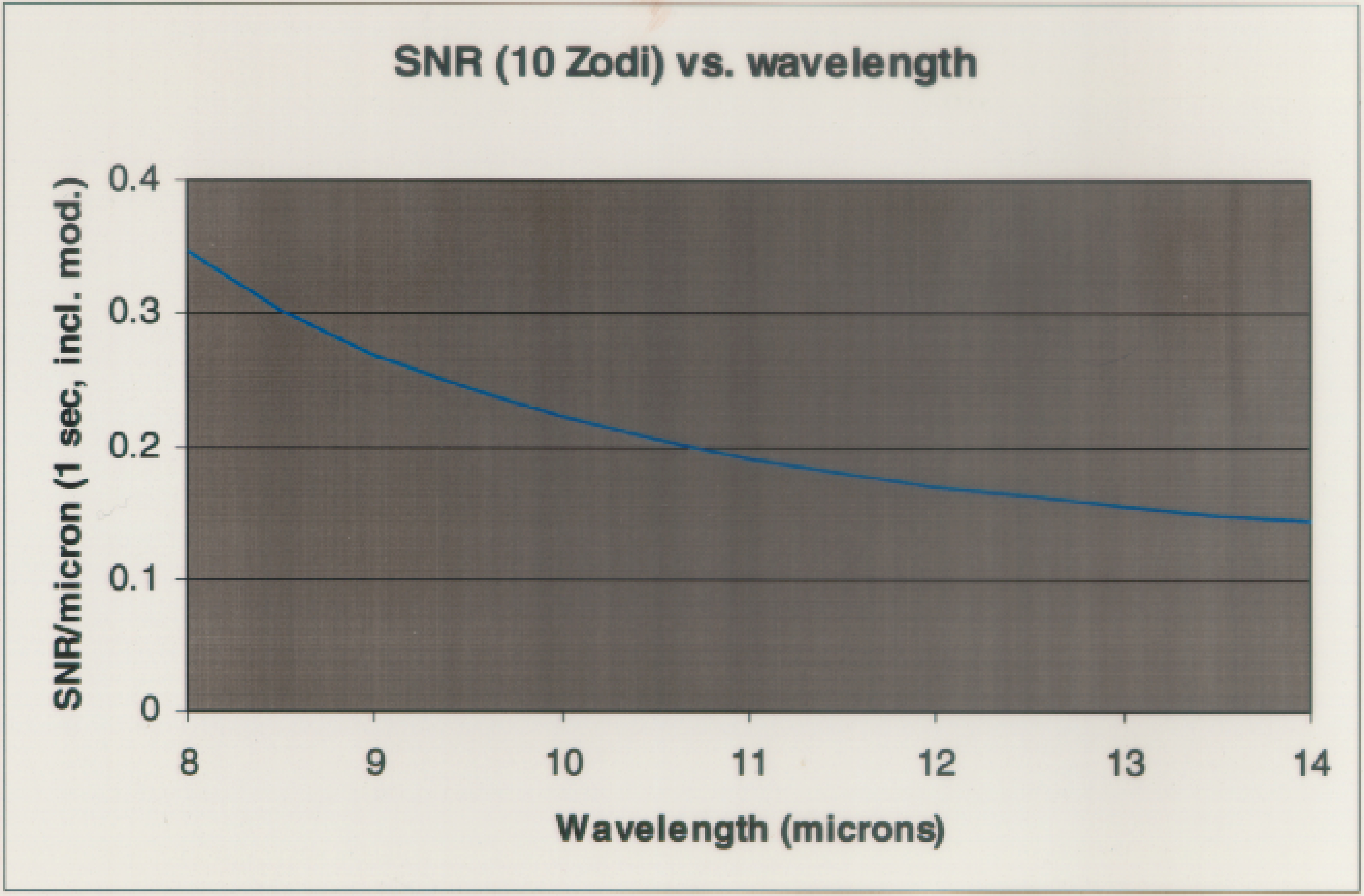



Nulling of G2 star at 10 pc dist. on K1-K2 baseline
Rejection ratio
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
8
9
10
11
12
13
14
Wavelength (microns)



Stellar leakage signal (2 Kecks)
Photon flux (N/s/micron)
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
8
9
10
11
12
13
14
Wavelength (microns)


Background Flux (2 Kecks)
Photon Flux (N/s/micron)
1.40E+10
1.20E+10
1.00E+10
8.00E+09
6.00E+09
4.00E+09
2.00E+09
0.00E+00
8
9
10
11
12
13
14
Wavelength (microns)



SNR (10 Zodi) vs. wavelength
SNR/micron (1 sec, incl. mod.)
0.4
0.3
0.2
0.1
0
8
9
10
11
12
13
14
Wavelength (microns)

Pessimistic SNR for exozodiacal signal

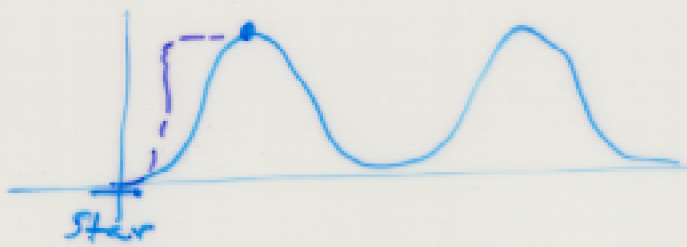
- Optimistic value: SNR(4 hr; 10 Zodi; including modulation) = 50
- Pessimistic case: $\lambda = 10\ \mu m$, $\Delta\lambda/\lambda = 0.3$, emissivity = 0.65, total system efficiency = 0.046, cold throughput = 0.14, $A\Omega = \lambda^2$
- **Detection rates:**
- G star at 10 pc (2 Kecks) = 9e7 photons/s
- Stellar leakage thru null = 9e4 photons/s
- 10 solar zodis (2 Kecks) = 8e4 photons/s
- Background (2 Kecks) = 1.8e10 photons/s
- Noise (1 sec) = 1.35e5 photons
- SNR (1 sec; 10 solar Zodi; including modulation) = 0.3
- Pessimistic case: For emissivity at dewar = 0.65, SNR = 36
- Use only 9 m diameter; pessimistic SNR drops to 25

Signal Modulation

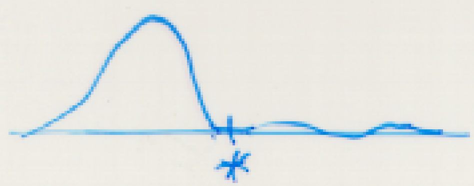
- Baseline rotation (slow): (Theory)
  fringes sweep across zodi/planet
- Spatial chopping: (LBT)
  nulling removes star; chop on/off zodi/planet
- OPD modulation for multiple baselines (Keck, TPF)
  many variations: rapid scan, $\lambda/4$ OPD offsets

Multiple Baselines:

- Want Deeper, Broader Null,
  but rapid rise in transmission
  to see planets



- Multiple baselines provide θ^4, θ^6 Nulls
- Want to break symmetry of fringes,
  - to tell on which side of the star the planet lies



The Future

- Broaden BW
- Move to MIR
- 2 Polarizations
- White Light Stabilization
- Control Architectures
- Do it at high altitude
- Do it in space.